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**The Deep Impact Mission : Opening a New Chapter in Cometary Science**

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## THE DEEP IMPACT MISSION : OPENING A NEW CHAPTER IN COMETARY SCIENCE

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### ABSTRACT

Deep Impact will impact the comet Tempel 1 on July 4, 2005, with a 450 kg smart impactor, at a relative velocity of over 10 km/s. The impact energy of 24 gigajoules is expected to excavate a crater over 20m deep and 100m wide. The impact event will be clearly visible from small telescopes on Earth, especially in the IR bands. The resulting crater development will be viewed by a Flyby Spacecraft for a period of up to 16 minutes, including IR imaging and high-resolution visible images of the ejecta and the fully-developed crater. This science data set will provide unique insight into the materials and structure within the comet (underlying the relatively aged surface), and the strength of the surface. Secondary observations include the coma dust environment, optical properties, and nucleus morphology. The Deep Impact program includes a one-year formulation phase followed by a 33-month implementation phase, which includes one year of integration and system test, and launch. This is followed by an 18-month cruise until encounter. The entire program budget is capped at \$273M (real-year dollars), including management reserves, and BATC and University of Maryland contributions. A thorough risk management program is designed to assure that all science objectives are met, within programmatic constraints and including the large uncertainties of the cometary environment.

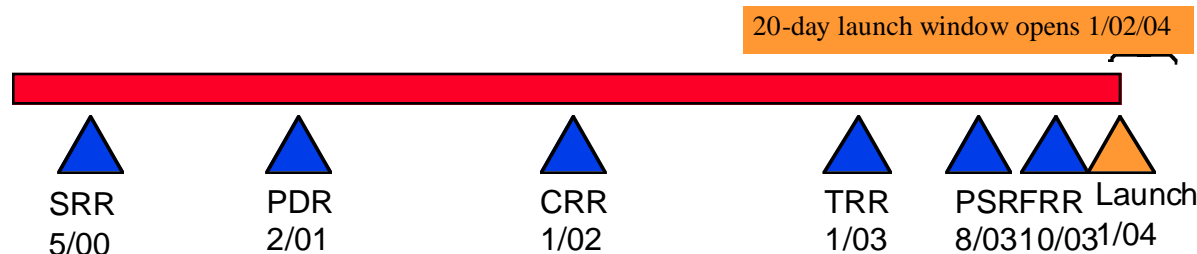
### PROGRAMMATICS

Deep Impact (DI) is a new NASA Discovery program, awarded in 1999 to a team comprised of University of Maryland (UMd), NASA Jet Propulsion Laboratory

management, system engineering, mission design, navigation, fault protection, and operations efforts, and Ball is responsible for development of the flight system and instruments, with JPL hands-on contributions in all areas. The management philosophy is a very lean, flat organization, co-located at Ball in Colorado and JPL in California. The distance between these two facilities is bridged by short, frequent trips, and heavy use of electronic media such as teleconferencing, e-mail, and web-based tools. Delegation of responsibility and authority to make technical decisions, and to meet cost and schedule constraints is pushed down to the subsystem level, to the highest degree possible.

### Schedule

The top-level DI schedule is shown in **Figure 1**. It shows a spacecraft and instrument development time of less than 3 years, including one year of integration and system test, and a 20-day launch window starting on Jan 2, 2004. Four months of slack is presently built-into the schedule. The development time supports design and implementation for 3 new instruments, new Flyby Spacecraft and Impactor designs, a new flight computer, new flight software, high-precision pointing and tracking capability for the imaging, state-of-the art autonomous navigation. All of these must address many complex issues resulting from the uncertainties in the near-comet environment. Development risk is mitigated in part by JPL's recent experiences with the highly successful Pathfinder and Deep Space-1 programs, which provide important heritage for the autonomous navigation and fault protection software. Ball Aerospace also has successfully developed 10 spacecraft in the last 13 years, on-cost and on schedules



(JPL), and Ball Aerospace and Technologies Corp (BATC). UMd is responsible for the overall program management and science, JPL leads the technical

shorter than DI. Together, this badgeless team expects to meet all science objectives within program cost and schedule constraints.

## Cost Caps

Being a NASA Discovery program, the DI budget is strictly cost-capped. The program proposed cost is \$273M (in real-year dollars), which includes spacecraft, impactor, and instruments development, launch services, ground system support, operations and science data analysis. To mitigate risk of exceeding this, the program will hold at least \$38M as management reserve. The mission was conceived from the beginning to live within the cost-constrained environment. The proposed science was focused on key issues that can be achieved within the cost limits. For example, we would like to determine the mass and, hence, the bulk density of the comet nucleus, but we could not find a robust solution within the cost limitations.

## SCIENCE OBJECTIVES

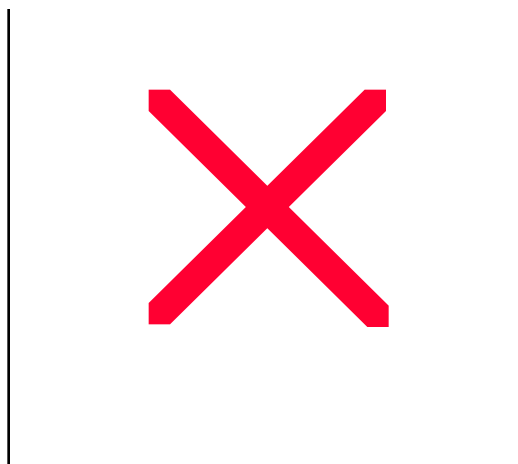
Deep Impact will provide key insights into the interior of comets previously unavailable from other missions. This will lead to insights into the development of our solar system, and understanding comets better in general; some of mankind's most ancient puzzles.

## Cometary Materials

Our knowledge of comets is dominated by a number of paradoxes. For example: Comets contain perhaps the most pristine, accessible material from the early solar system, but where is it in the nucleus? Comets appear to become dormant, but does the ice become exhausted, or is sublimation inhibited somehow? Which dormant comets are masquerading as asteroids? Coma gas observations are widely used to infer ices in protoplanetary disks, but what is the composition of the nucleus? Comet nuclei have been observed to break apart under small stresses, but is there strength at any scale?

The present state of knowledge of cometary nuclei size and albedo are derived almost entirely from observations of comet Halley, as shown in **Figure 2**.

Cometary nuclear surfaces are thought to be aged by multiple processes. Aging processes while in the outermost solar system (Oort cloud) are limited to cosmic rays and "warming" by passing stars and supernovae but just beyond Neptune they also include collisions and accretion of debris. Perhaps more importantly, near perihelion, the surface is changed by relatively rapid solar heating, which causes outgassing, ruptures from gas pressure, migration of volatile ices,

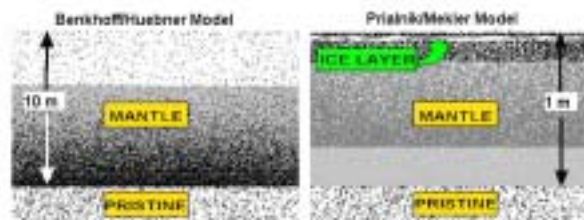


**Figure 2.** *Halley nucleus image from previous flyby provides basis for present knowledge of nuclei size and albedo.*

thermal stress fractures, and venting. These processes cause the surface layers to be dominated by lag and rubble layers that obscure observation of the mantle and pristine materials underneath. Various models show the depth of these outer coatings to range from one to many tens of meters, as shown in **Figure 3**.

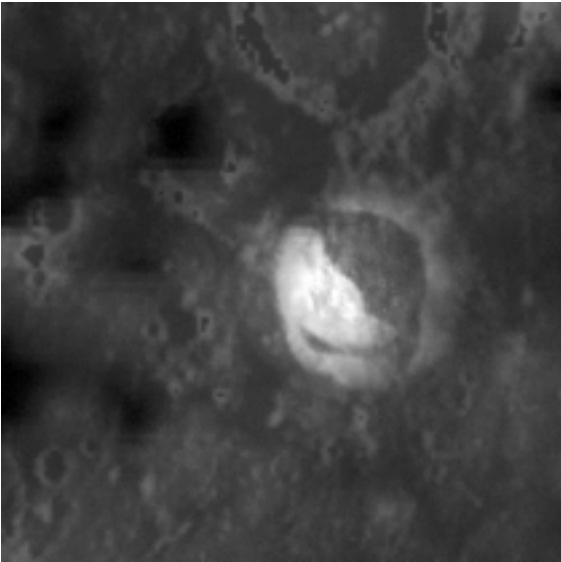
## Cratering

Cratering is a very effective and relatively simple method of exposing the nucleus mantle and pristine materials for observation. Observation of the crater



**Figure 3.** *Benkhoff/Huebner and Priainik/Mekler comet surface models differ in the sign of the density gradient near the surface.*

development process also yields additional information about the mechanical properties of the materials. Scaling from terrestrial craters and hypervelocity impact experiments provides models of the DI crater depth, which yields a baseline prediction of approximately 120 m wide by 25 m deep, and an excavation time of about 200 sec. Sample simulated crater images, as seen by the DI instruments, are shown in **Figure 4**. These images cover the extreme range of expected elevation angles, and also indicate the expected crater shape and shadowing effects. The instrument suite developed to produce these images is presented in a subsequent section.



**Figure 4.** Simulated crater images from extremes in expected range of elevation angles.

#### Ground-Based Observations

The impact event will be timed to be easily observable from Earth, from multiple observatories. The primary observatories will be in Chile, with supplementary observations from the whole hemisphere (particularly from the Canary Islands) as well as space-based resources such as HST and (maybe) SIRTf. Imaging data types will include UV, visible, and IR bands, spectroscopy will include far UV, UV, visible, and IR bands, and photometry science will include bands from X-ray through far-IR. Together with the short-range observations made by the DI flight system, these data will allow determination of the relative abundance of cometary materials such as  $\text{H}_2\text{O}$ ,  $\text{CO}$ , and  $\text{CO}_2$ .

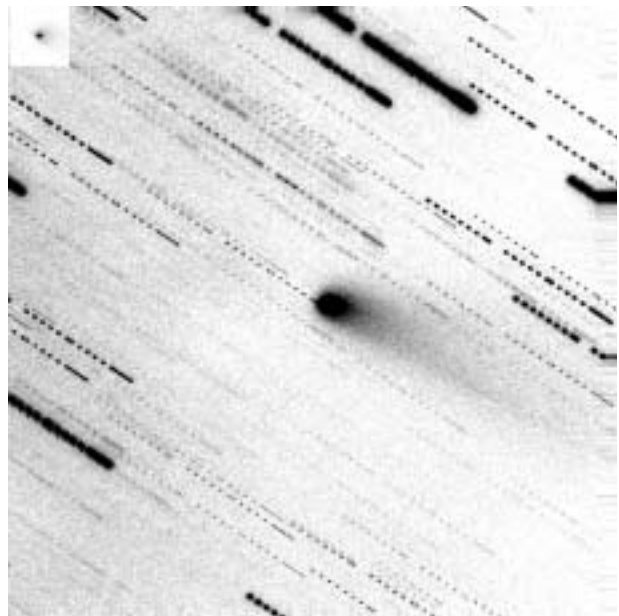
#### Comet Environment Models

The very same unknowns that make comet exploration extremely rewarding, also make it technically challenging. The challenges include modeling the visible appearance of the nucleus, to aid in development

of the autonomous-impacting navigation algorithms. The nucleus shape may be rather irregular due to accretion, which causes light and dark patches. For visibility from the Flyby spacecraft, the Impactor must hit in a lighted area.

Ground-based observations of Tempel 1 have been made during the 2000 apparition using the UH 88-inch and Keck 10m telescopes to assist in characterizing the environment that DI will face during the next apparition in 2005. A visible image taken on Sept 9 at a range of 2.6 AU, 8 months after perihelion, is shown in **Figure 5**. This indicates a much dustier environment than previously expected, probably due to the presence of residual large dust particles ejected near perihelion. The current best estimate, based on a very preliminary analysis of the data from August 2000, is that the comet has dimensions of roughly 2.5 by 7 km, somewhat smaller than estimated at the time the concept study but also somewhat more highly reflective.

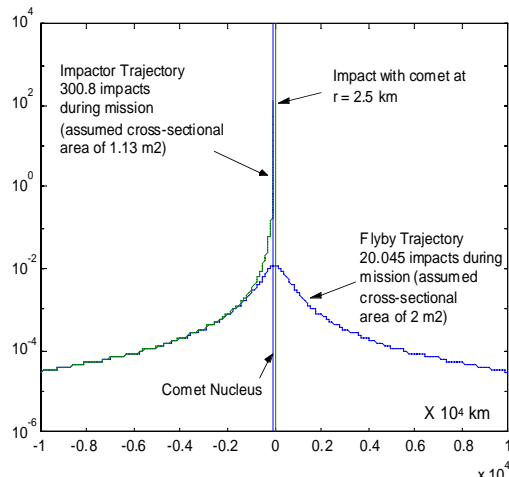
Modeling of the dust particle size distribution is critical



**Figure 5.** Recent visible image from University of Hawaii 88-inch telescope shows high dust content.

to the DI flight system design process, since it determines attitude control capabilities and shielding requirements. Curves of the currently-predicted dust flux are shown in **Figure 6**. The horizontal scale covers the time between Impactor impact, closest-approach by the flyby spacecraft, and egress from the coma. The Impactor is expected to experience many dust collisions prior to hitting the nucleus, while the Flyby Spacecraft is expected to experience a relatively small number. Uncertainties in the data underlying these curves, and their associated statistical probabilities, create a range of flux that covers an order of magnitude. High-fidelity performance simulations of the flight system in this

range of environments shows that the Flyby Spacecraft shows a good probability of maintaining high-quality pointing control throughout the flyby, whereas the Impactor attitude control may be lost shortly prior to impact.



**Figure 6.** Expected dust flux profile is highly nonlinear due to inverse-square density model.

## MISSION DESIGN

### Selection of Tempel 1

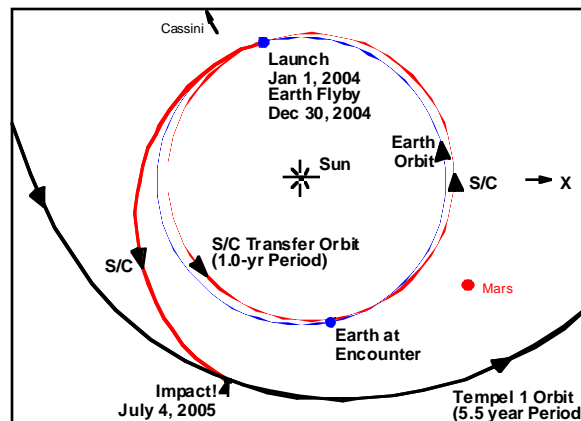
The comet Tempel 1 (officially designated 9P/Tempel 1) is the selected target for the Deep Impact mission based on an excellent fit with the scientific objectives and its accessibility for launches from the Earth at relatively low energy. With an orbital period of 5.5 years and a descending node near its perihelion at 1.5 AU, Tempel 1 can easily be reached for a flyby mission and has excellent Earth-based observability at its 2005 apparition. The trajectory geometry allows a launch mass sufficient for a 450-kg impactor and favorable approach conditions, including the <64 deg solar phase angle (angle of sun from the zenith at the sub-spacecraft point), and the desired impact speed >10 km/s to ensure vaporization of the Impactor and creation of a suitably large crater. Other key criteria leading to the selection of Tempel 1 are the relatively low dust hazard, and the short range to Earth at impact (0.9 AU). Several other targets, including Tuttle-Giacobini-Kresak, were considered, but Tempel 1 has the best combination of encounter conditions, observability, and accessibility in the time period of interest.

### Launch Vehicle

DI will use the 2925 version (formerly termed the 7925H) of the well-proven Delta II launch vehicle, procured by Kennedy Space Center under the NASA

Launch Services contract. This LV is expected to provide a launch mass of at least 1174 kg to the required injection energy of  $11.8 \text{ km}^2/\text{s}^2$ . The DI Flight System (FS) is sized to fit within the Delta 9.5-ft fairing, and to be compatible with the Delta in all other respects.

### Earth-to-Earth Cruise Phase



**Figure 7.** Mission trajectory includes launch, Earth-to-Earth Cruise, and encounter phases.

The complete mission trajectory is shown in **Figure 7**. The Earth-to-Earth cruise phase provides over a year to fully characterize, calibrate, and test the FS. A swing-by of the Earth/moon system will occur in January 2005, allowing for calibration and test of the encounter software and instrumentation.

### Encounter Phase

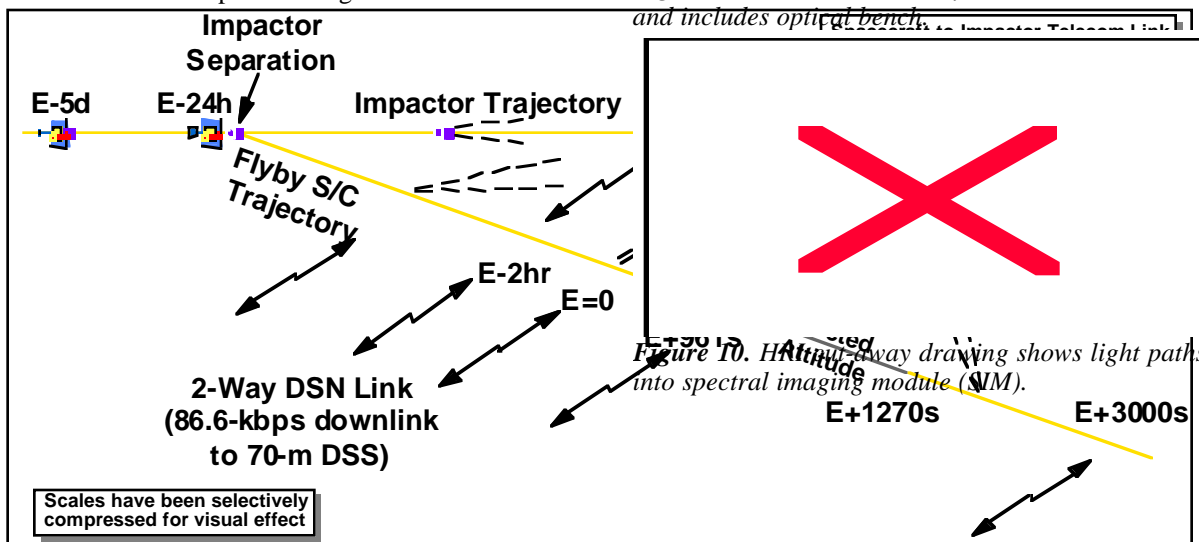
The encounter phase includes optical navigation prior to Impactor separation. Following separation, the Flyby spacecraft will slow itself relative to the Impactor by 120 m/s, which also includes a small cross-track component to provide the required 500-km flyby distance. The comet environment (primarily albedo and jets) will then be characterized by high-rate optical imagery downlinked in real-time, processed on the ground, and if necessary, uplinked to the Flyby Spacecraft and cross-linked to the Impactor. At the time of impact, the range to the comet from the Flyby will be approximately 10,000 km. The Flyby spacecraft instruments observe the impact event (crater and ejecta) temporally, spatially and spectrally. The long range at impact provides 16 minutes of imaging time, which provides a 200% margin over the predicted crater development time. At the end of the imaging sequence, the Flyby Spacecraft will have pitched 45 deg, and then be in a “shield-mode” attitude to enter the higher density dust region and for crossing the more hazardous orbital plane, as shown in **Figure 8**.

## FLIGHT SYSTEM

The DI Flight System is composed of the Instruments, the Impactor, and the Flyby Spacecraft.

### Instruments

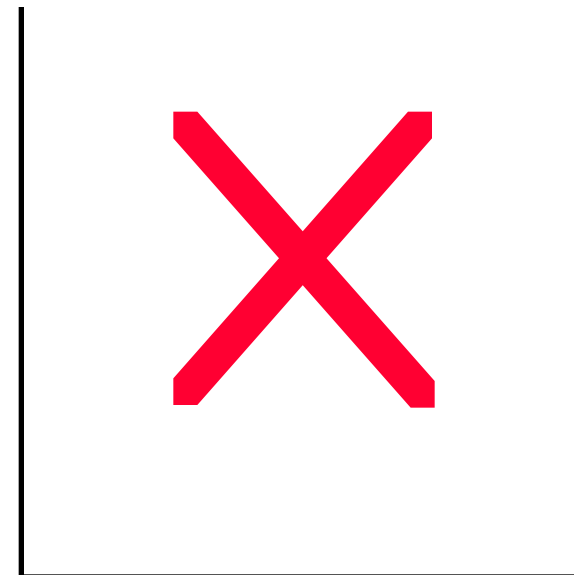
There are 3 primary instruments, two of which are shown in **Figure 9** and are accommodated by the Flyby Spacecraft. The High Resolution Instrument (HRI) is shown in more detail in **Figure 10**, and uses a 30 cm aperture to support a Full Width Half-Max (FWHM) performance of 3.4m at closest approach. The visible CCD response spans 0.3 to 0.95  $\mu\text{m}$  imaging, while the IR spectrometer spans 1 to 4.8  $\mu\text{m}$ . A scan mirror is used to build a multispectral image cube. The Medium-



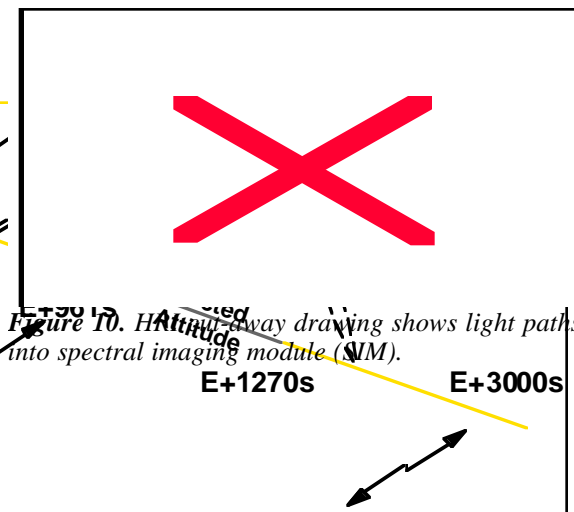
**Figure 8.** Encounter design supports imaging requirements with acceptable hazard to Flyby Spacecraft.

Resolution Instrument (MRI) design is similar to the HRI, although at 5 times lower spatial resolution, and supports optical navigation and provides functional redundancy to the HRI.

The MRI internal design is similar to the HRI. Light is split by a dichroic beam splitter, and then routed both through a filter wheel to the visible CCD, and to the scan mirror for IR imaging. Instrument electronics then pipe the image and spectral data directly to a solid-state mass-storage device, and also selected high-priority data to the Flyby spacecraft for near-real-time downlink. The Impactor carries the third instrument, the Impactor Targeting System (ITS), which to reduce cost and risk, is nearly identical to the MRI.



**Figure 9.** Instrument assembly is stand-alone module and includes optical bench.



**Figure 10.** HRI light path drawing shows light paths into spectral imaging module (SIM).

### Impactor

An exploded view of the Impactor configuration is shown in **Figure 11**. It is designed to nestle within the Flyby spacecraft, and also carry the launch loads into the LV adapter. The Impactor will use the ITS and advanced JPL software to autonomously perform any course corrections required to assure impact in a lighted area. A UHF cross-link capability is provided to transmit close-up images of the comet surface prior to impact, and also provides contingency commanding to the Impactor.

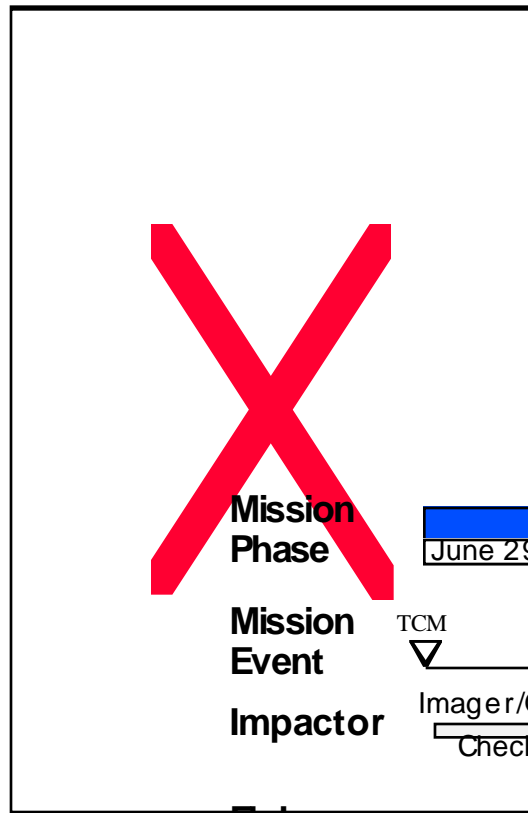


Figure 11. Impactor exploded view shows FS interfaces.

**Mission Phase**

**Mission Event**

**Impactor**

**Flyby Spacecraft**

**DSN Tracking  
34m Coverage**

inside, is shown in **Figure 12**. The instrument assembly can be seen mounted to the side of Flyby Spacecraft. Shielding is added to what appears to the “bottom” side of the spacecraft in this view, to survive the coma passage following closest approach and the end of imaging (this accounts for the 45-deg rotation of the instrument boresights relative to the vehicle figure axis). The Flyby spacecraft is entirely redundant, and features a very-high throughput RAD750 CPU and 1553 data bus-based avionics architecture, and a high-stability pointing control system.

#### Encounter Critical Sequence

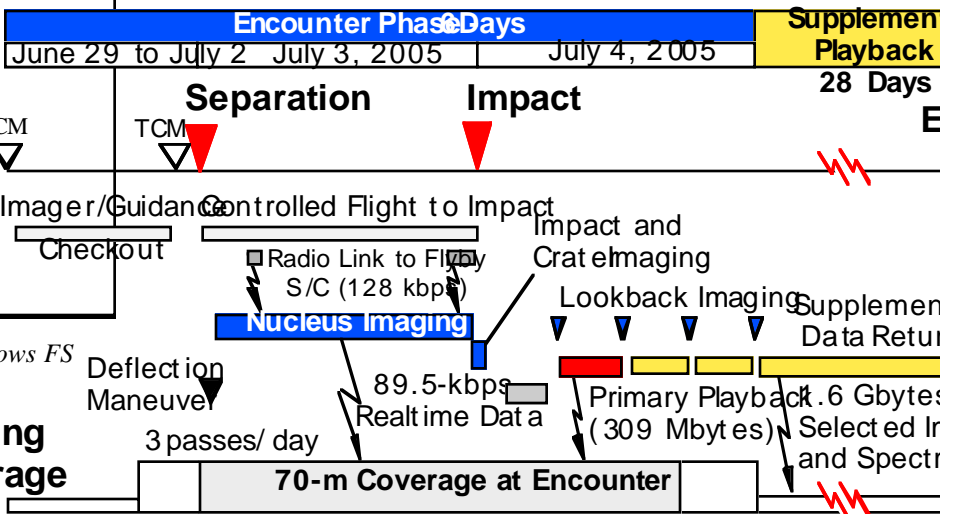


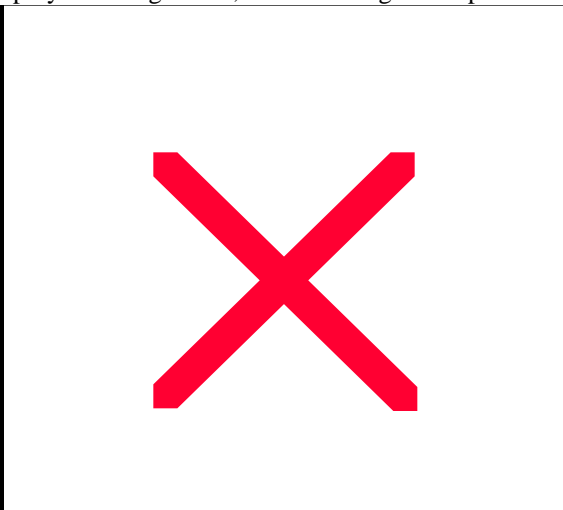
Figure 13. Encounter timeline shows choreography of numerous critical events.

The Impactor design includes approximately 300 kg of copper, which will help create the large crater without spectral contamination of the immediately post-impact observations; particularly the earth-based measurements of all types.

#### Flyby Spacecraft

The Flyby spacecraft configuration with solar arrays deployed during cruise, and including the Impactor

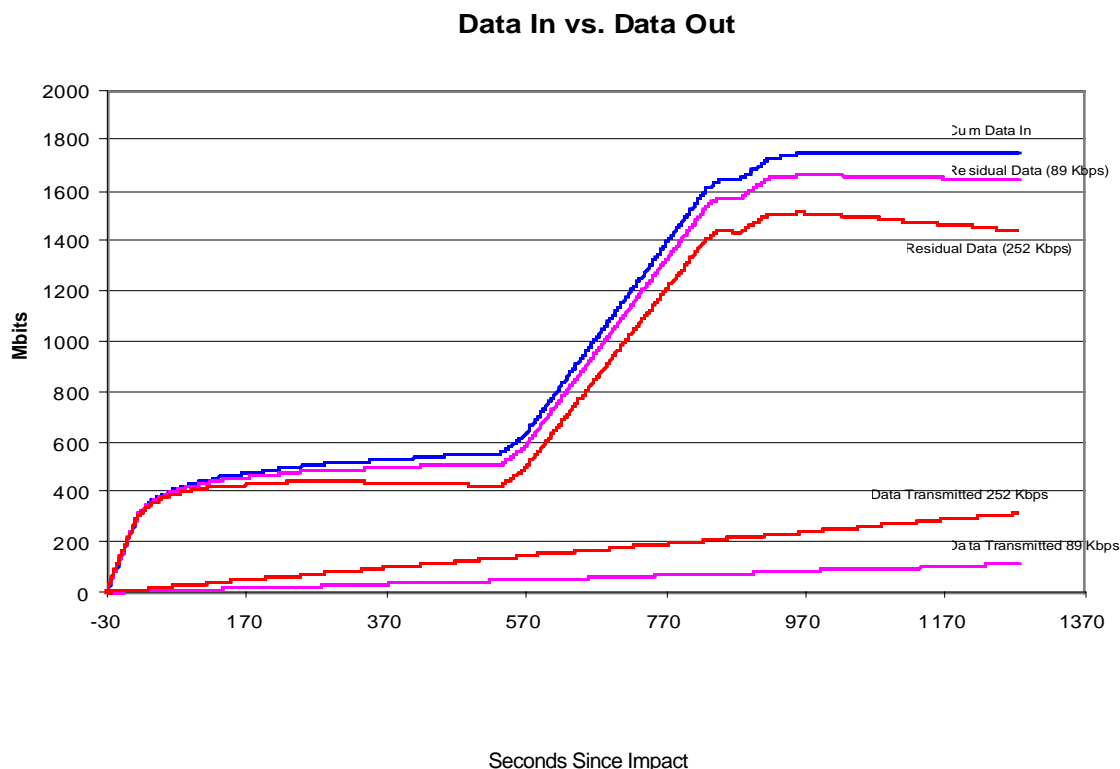
The comet encounter has been deemed a “critical sequence,” meaning that the FS must have sufficient autonomy to correct faults, and proceed with the mission without ground intervention. The encounter timeline is shown in **Figure 13**, including communications and imaging sequences of both the Impactor and the Flyby spacecraft.



During the encounter final imaging sequence, the rate of data collection from the instruments is far higher than can be downlinked in real-time, as shown in **Figure 14**. Downlink rates of 86 to 300 Mbps are presently under consideration, but even the highest rate can only return a fraction of the data. Consequently, most of the data is stored in four separate 1.6 Gbyte solid-state recorders,

modes and effects analyses, redundancy, and other standard processes.

Development risks are those that threaten program schedule and cost constraints, via unexpected technical issues. DI implements a thorough process of ranking the magnitude of these risks as the product of their cost



**Figure 14.** Plot of data taken by instruments, downlinked in real-time, and the residual for storage.

(1 each for the IR and optical detectors of both the MRI and HRI). This data is then selectively played-back over a period of a month following near-nucleus coma passage and also following the completion of “lookback” imaging to observe the other side of the nucleus.

## RISK MANAGEMENT

The entire family of Discovery programs are collectively low-risk, via distribution of limited funding to a multitude of relatively low-cost, narrowly-focused specialty missions. DI risk management implements several approaches to assure that mission requirements are met, within the challenging comet environment, and also within program cost and schedule constraints.

### Mission Risks and Development Risks

Mission risks in terms of FS reliability are being addressed via high-quality mission assurance programs at both Ball and JPL, including parts programs, failure

or schedule impact, and their probability of occurrence. Risks are re-assessed monthly by the program management and system engineering teams. Each risk is carefully defined, ranked, and assigned an “owner”. We mitigate each risk by pro-actively trying to reduce both its probability of occurrence, and its potential impact. Back-up contingencies are also defined, with clear decision and closure criteria.

Development risks are also mitigated by the maintenance of good system performance margins, as shown in **Figure 15**. The parameters listed here have been carefully selected to cover all of the expected areas where FS growth over time may be expected to consume limited available resources. Each of these parameters are updated monthly, including their constituent members (e.g., Flyby, Impactor, and Instrument masses separately from LV performance), and are plotted for trend analysis by the system engineering team.

The dominant risks at this time relate to the uncertainties in the comet environment discussed above, and our confidence in the flight system ability to

successfully impact in a lighted area, to provide pointing control and stability sufficient for the highest-possible image quality, and to survive the dust environment overall. All of these issues are being addressed via the concept of system robustness.

### System Robustness

FS robustness is achieved by detailed assessment of performance margins in key areas, especially those that represent the system performance during the critical encounter sequence (many of the performance margins listed in Figure 15 are defined in this manner by driving sequences). The DI FS will be as robust as possible, in the presence of the uncertain comet environment, and the program cost and schedule limitations. This means that special attention is presently being paid to autonomous navigation performance, end-end system image quality performance, robust guidance and control, maximizing real-time data downlink capability, intelligent dust shielding design, and autonomous fault protection and recovery systems.

### CONCLUSIONS : IS DEEP IMPACT FASTER, BETTER, CHEAPER?

Deep Impact will provide previously unmeasurable data addressing the most basic questions about comet nuclei. It will do this by blending high technologies, where required, with existing capabilities, to develop a very robust Flight System. The FS will be supported by a broad ground network providing operations and science observations, also increasing system robustness. The program is presently on-track for a 3-year development including one year of integration and test prior to launch. The entire system cost will be well under the Discovery program cap of \$300M including launch vehicle.

To determine if Deep Impact is “Faster, Better and Cheaper” we need to establish references to compare

against. NASA set up the faster reference in the Discovery groundrules, we have to complete phase C/D in less than three years. DI will go from PDR to launch in 35 months including four months of schedule slack. DI is faster than the older planetary programs that took many years longer than the 3 years for Discovery.

By definition DI is cheaper. We were given a \$300M (1999 dollars) cost cap and our mission is estimated at \$274M (real-year dollars), including launch vehicle and reserves.

But is DI better? “Better” must be measured in two components, science return and performance in development and flight. The science return is clearly world-class and unique. We have highly focused science that provides a stepping stone to a fuller understanding of the solar system. The measure of performance in development and flight is best gauged (other than in hindsight) by the steps being taken to assure quality and mission success. These steps include the integrated BATC/JPL technical team, strong systems engineering, aggressive software validation, extensive subsystem and system testing and a commitment to keeping the best of both the JPL and BATC cultures while innovating to meet the mission objectives within the program constraints. We have an action-oriented team that is staffed by an experienced team from Ball’s recent Multi-Spectral Thermal Imager, QuikScat and GFO programs and JPL’s Cassini, Pathfinder and DS-1 programs. Ultimately, when we return the Deep Impact data, the public and history will judge if DI was truly “better”.

### ACKNOWLEDGEMENTS

This paper is based on the work of the entire DI team, which the authors wish to recognize. We especially acknowledge Brian Muirhead and Bill Blume of JPL, for their willingness to review and help edit this text at the last minute prior to publication.

	Epoch	SRR Guideline	SRR (5-16-00)	as-of 7-18-00	Present as-of 8-15-00	PDR Guideline (2-27-01)
mass		25	20%	31%	31%	20
ed on worst case maximum mass)		20	26%	22%	22%	20
asurements and CMD outputs (H/W)		20	50%	20%	20%	20
rocessing time and data bus capacity		60	425%	425%	425%	50
Memory, NVM		60	128%	128%	128%	50
emory (science)		40	>100%	>50% (TBR)	>50% (TBR)	35
list. & pyro relays		25	38%	38%	38%	20
eneration (S/A) margin during TBD ) sequence		25	25%	32%	32%	20
ry capacity during driving sequence		40	75%	184%	184%	40
r battery capacity during driving sequence		30	33%	75%	75%	30

1 is defined as the per cent of allocation unused, i.e. (allocation-current best estimate)/CBE.

outer sizing margins shown for typical mix of new/re-used code (entirely new code should have higher margins, rely re-used code may have less)

/ capacity allocation is the allowable discharge (amp-hours), not the name-plate or the maximum possible.

